

Improving the Navy's Passive Underwater Acoustic Monitoring of Marine Mammal Populations

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LONG-TERM GOALS

The long-term goals of this research effort are to improve the Navy's passive underwater acoustic monitoring of marine mammal populations. A major focus in this project is on further enhancing the ability to estimate environmentally-calibrated calling density (calls per unit area per unit time) obtained from raw detections of calls in underwater acoustic recordings. The efforts in this program also support the Ph.D. research of a graduate student in marine bioacoustics and ocean acoustics at the Scripps Institution of Oceanography.

OBJECTIVES

The specific objectives of this project have been: 1) to further develop the methods for accurately estimating the densities of low-frequency-calling marine mammal species using passive acoustic monitoring, with application to obtaining density estimates of transiting humpback whale populations in the Southern California (SoCal) Bight, 2) to incorporate detection theory formalism into the acoustic density estimation procedure in order to minimize the variance of the density estimates, 3) to apply the numerical modeling methods for humpback whale vocalizations to understand distortions caused by propagation of humpback calls west of Kauai, Hawaii, and 4) to conduct spatial statistical analyses and correlation analyses of marine mammal and other bioacoustic sounds in the SoCal Bight with man-made underwater sounds, with physical properties of the environment, and with fields relevant to the biological productivity of the water column. The work in this project has been heavily leveraged with other ongoing programs and efforts, as discussed in Related Projects below.

APPROACH

Passive underwater acoustic monitoring of marine mammal sounds is the Navy's primary method for characterizing the presence, distribution, and number of marine mammal species in several different environments. This project addresses several aspects of this monitoring effort in order to improve the scientifically relevant information that can be obtained from the recordings. The overall approach is to extend the research thrust of correcting for environmental properties in detections of marine mammal

calls in passive underwater acoustic recordings, and to use these environmentally-corrected call detections to learn more about the animals themselves. Detected call counts are determined not only by the animals' calling characteristics, but also by the properties of the underwater environment in which the calls are recorded. First, propagation through the ocean environment can have a significant distorting effect on the recorded calls. This distortion can be strongly site dependent and dependent upon time of day and season. Second, the sounds from all other sources in the ocean ("noise") directly affect the ability to detect calls of interest. The characteristics and level of noise also can be strongly dependent upon recording location and time. By correcting the detected call counts for these environmental effects, along with assigning uncertainty to the resulting environmentally-calibrated call density estimates, scientifically meaningful conclusions about the calling characteristics of the whales themselves can be obtained.

The specific approach being followed to accomplish objectives 1-4 above is listed below.

- 1) Detailed numerical modeling of baleen whale call propagation (as in Helble et al., 2013a) has been conducted at a number of "High-frequency Acoustic Recording Package" (HARP) monitoring sites off the California coast. The low-frequency content of baleen whale calls makes it imperative to account for the frequency-dependent, complex waveguide effects in call propagation. The best available water column and ocean bottom archival information presently was assembled to support this modeling effort. The most recent version of the C code for the Range-dependent Acoustic Model called "Peregrine", a parabolic equation-based numerical model developed by Richard Campbell and Kevin Heaney of OASIS for optimal numerical efficiency, was the basis of most of the numerical modeling. In addition, a ray-based numerical model was written and tested to explain some interesting features of fin whale calls in the near field. An extensive effort was made to verify that the synthesis of baleen whale calls in the time domain was performed correctly. Another goal was to extend the modeling to source-receiver ranges greater than 20 km for lower-frequency baleen whale calls and in certain situations where efficient long range propagation can occur (e.g., at Hoke Seamount and in certain basin-type environments). Baleen whale calls were detected in the HARP data collected at these sites using the Generalized Power Law (GPL) detector (Helble et al., 2012) and the resulting call counts were calibrated for environmental effects using the estimated probability of detection (re Helble et al., 2013a,b). The corresponding statistical uncertainties of the calibrated call densities also are being calculated (as presented in Helble et al., 2013c and Helble et al., 2015). These calibrated call density estimates then can be converted into animal density estimates, through normalization by an estimate of the average call (cue) rate (Marques et al., 2009). This work is being coordinated with Tyler Helble's 322-MMB project "Obtaining Cue Rate Estimates for Some Mysticete Species using Existing Data" in order to use the best available call rate estimates.
- 2) A main component of incorporating detection theory formalism into the acoustic density estimation procedure was completed early last year, and the results were included in Helble et al., 2013c and Helble et al., 2015.
- 3) Numerical modeling was conducted of the propagation of humpback whale vocalizations originating in the shallow water reef areas just west of Kauai, Hawaii to the Pacific Missile Range Facility (PMRF) hydrophones in deeper water offshore (re Fig. 1). The approach used the Peregrine code and followed that in 1) above. The waveform distortions caused by propagation were simulated in order to determine whether or not they can be used to help localize the calling

animals. Application of waveguide invariant methods has been investigated as part of this effort. As expected, propagation distortions were particularly strong over the shallow portion of the path, the biogenic reef off fringing Kauai, but multipathing in the deeper part of the propagation path also had a significant effect. The sediments on the biogenic reef are a composite of coarse-grained carbonate and fine-grained volcanic sediments (Fig. 1b) that are poorly sorted compared to the well sorted, fine-grained quartz sediments of terrigenous origin often found in other shallow water environments.

- 4) Some new statistical approaches to spatial and spatiotemporal statistical analyses and spatial correlation analyses have been applied to marine mammal vocalizations in the Southern California Bight (D'Spain et al., 2014). These statistical procedures hold significant promise for identifying patterns they may have biological significance and for providing new information on marine mammal behavior (D'Spain et al., 2014). These analyses have been greatly aided by the ability to localize calling marine mammals with certain data acquisition systems. At the same time, many of the methods originally planned to be applied in this effort pertain only to examination of the *linear* statistical relatedness between observed quantities. Recently-published results indicate that when nonlinear relationships exist between observed quantities, statistical correlations and other measures of linear relatedness can be very misleading (Sugihara et al., 2012). Nonlinearity is a common aspect of the relationships between physical and biological observables in most ecosystems. Therefore, these newly-developed nonlinear techniques have been examined for applicability to the study of marine mammal calling behavior in relationship to other properties of the marine environment, including anthropogenic sound sources.

The graduate student who was working in this project in 2014 in her first year in the Applied Ocean Sciences curricular group decided to move onto another research project after successfully passing her Departmental exam at the end of spring quarter, 2014. Fortunately, as the recipient of a Scripps Regents Fellowship, she came at no cost to the program that first year. A suitable replacement graduate student, interested in the fields of bioacoustics and ocean acoustics, was brought onto this project in 2015. She also is the recipient of a Scripps Regents Fellowship and so comes at no cost her first year. She holds joint undergraduate degrees in marine biology and physics, with minors in math and ocean sciences. In addition, a senior undergraduate student from the UCSD department of electrical engineering has been working with our research group this past year. His initial research focus has been learning about the GPL detector and using it on our passive acoustic marine mammal monitoring data sets. Presently, he is involved in comparing the GPL performance to matched-spectrogram-based detectors for detecting and classifying transient sounds of biological origin. The GPL detector is based on a power-law processor, which is the optimal detector for transient signals when no *a priori* knowledge of the arriving signal exists. The family of power-law processors includes the energy detector. However, for stereotyped calls where propagation effects are not too strong, a matched-spectrogram-based detector may have better performance.

The work in this project was leveraged with other ongoing programs, listed in Related Projects below.

WORK COMPLETED

Numerical modeling out to 100 km range in 1-deg azimuthal steps and 10-m steps in depth was conducted for selected HARP sites in the Southern California Bight. This modeling was performed for the frequency band of blue and fin whale calls (10-200 Hz) as well as the frequency band relevant to humpback whale calls (120-960 Hz). The approach to broadband waveform simulation was further

developed to eliminate numerical artifacts that can arise with the parabolic equation approximation, and verified using simplified (homogeneous whole-space ocean) environments. Sensitivity analyses were conducted in order to determine which property(s) of the ocean environment play the most important role in determining the underwater acoustic propagation characteristics in various baleen whale call bands. Most of the numerical modeling was performed using the Peregrine parabolic equation-based code, after beginning the effort with an earlier version (CRAM) which had become outdated and no longer supported. In addition, some modeling was done with an in-house-developed ray tracing code to better understand which components of the field contributed to certain aspects observed in the acoustic recordings and to better understand the sensitivities of travel times to changes in the ocean. A wavenumber integration program (OASES) to appropriately model the acoustic field in the near field (within a few water depths in range) from the acoustic sources.

To support the numerical modeling, data bases of environmental properties and publications on previous research on ocean acoustic propagation offshore southern California were consulted for the relevant information. Of particular interest was information necessary to create geoacoustic models of the ocean bottom/sub-bottom using Hamilton's empirical equations (Hamilton, 1980). Although a few areas in the Southern California Bight have been well studied, and useful information on various properties of the ocean bottom is readily available, the uncertainty in the geoacoustic properties is the largest contributor to the error bounds on the estimates of environmentally calibrated call counts over the frequency band of baleen whale calls.

Note that the computer code for performing all steps required to environmentally calibrate raw detected call counts in single omni-directional fixed sensors for baleen whales was rewritten, enhanced, and documented as part of our LMR project. This code also was used to environmentally calibrate the detected call counts in this project.

Passive acoustic recordings at HARP sites M, N, and H covering all seasons were acquired from John Hildebrand's Whale Acoustic Group. These data have been combined with those from HARP sites in the Santa Barbara Channel and at Hoke Seamount (discussed in Helble et al., 2013a). In addition, disks containing a few days of data recorded from the bottom-mounted hydrophones at the Navy ranges at PMRF and SCORE range have been acquired. A program to transcribe these data from their recorded binary format into one useable with Matlab and in-house processing software was written, and all SCORE data have been converted.

The effort at incorporating statistical detection theory into animal density estimation from passive acoustic recordings was completed. In addition, a formal statistical framework for determining the uncertainty in the estimates of environmentally calibrated call counts in the baleen whale frequency band was derived (Helble et al., 2015a). The uncertainties associated with *relative* density estimates were compared to those for *absolute* density estimates, both for baleen whales and odontocetes. The results from this effort presently are being written up for publication (D'Spain et al., 2015).

The statistics of animal call distributions in space and time were studied, both for single calling animals and for groups of animals. Some results from this effort are presented in the next section. The implications of nonlinearity in the relationships between marine mammal calling behavior and other properties of the underwater sound field and ocean environment have been examined.

Effort was spent on the theoretical development and geophysical inverse theory methods behind optimal localization with hydrophones having overlapping coverage. This effort supported the writing

of a paper on 2D localization of calling humpback whales on the Pacific Missile Range Facility published in the Journal of the Acoustical Society of America (Helble et al., 2015). Localization was extended to 3D (depth), and a formal evaluation of the sources of bias and variance in the estimates was developed and written up for publication (Ierley et al., 2015). Two methods of performing an in situ calibration of arrays with small inter-element spacings with respect to an acoustic wavelength were developed and tested in simulation. These methods hold great promise for improving localization of low-frequency baleen whale calls with arrays designed for the high-frequency odontocete frequency band. They presently are being tested on multi-channel HARP data and on data recorded on bottom-mounted hydrophone arrays off the southern California coast in 1999, and the results will be prepared for publication in the Journal of Oceanic Engineering. Finally, a paper to Endangered Species Research on the statistical uncertainty in calibrated call count estimates, and the major sources of this uncertainty, is being submitted (Helble et al., 2015a). In addition, two abstracts were submitted for presentation at two Acoustical Society of America meetings (D'Spain et al., 2014; D'Spain and Pagniello, 2015) and two presentations were given at the June, 2013 "Detection, Classification, Localization, and Density Estimation" workshop in St. Andrews, Scotland (D'Spain et al., 2013; Helble et al., 2013c).

RESULTS

Many of the efforts in this program were a continuation and extension of the work performed in previous projects. Most of the results from those efforts appear in Helble et al., 2012; 2013a; 2013b. A few results in this project are:

- The uncertainties in *relative* call density estimates can be significantly lower than those for *absolute* call density estimates under certain conditions. In particular, for beaked whales, the sounds received by bottom-mounted receivers are dominated by direct-path propagation over depth ranges in excess of a few hundred meters, so that the propagation characteristics are generally independent of time and location. In addition, the background noise levels in the beaked whale frequency band often is determined by the electronic self-noise of the recording system rather than naturally-occurring ocean noise, and so is time- and site-independent. Under these conditions, relative density estimates are significantly more reliable and contain less bias and uncertainty than absolute estimates.
- Setting the detector threshold to a higher level in order to reduce the uncertainty in the estimated probability of detection (by reducing the areal coverage and therefore the impact of the uncertainty in ocean bottom properties) does not help reduce the overall uncertainty in the environmentally-calibrated call detection estimates. Rather, it only introduces a non-zero probability of false alarm (which equals zero when the areal coverage includes all detectable calls), and the associated uncertainty in the estimate of this probability.
- The statistical framework for calculating the bias and variance in the estimates of environmentally calibrated baleen whale call counts obtained from single, omni-directional sensors with non-overlapping coverage (now incorporated into Helble et al., 2015a) shows that the estimated variance at baleen whale frequencies is dominated by a) the variance in noise level, and b) the variance due to uncertainty in calling animal location. In contrast, the geoacoustic properties of the ocean bottom can be modeled as deterministic rather than stochastic, but the uncertainty in bottom properties results in a significant bias in the estimates in most cases. Whereas nothing can be done to reduce the noise variance (except possibly to choose alternative sensor deployment sites), sensors with directional capability (e.g., acoustic

vector sensors) and/or overlapping coverage reduce, or eliminate, the variance due to calling animal location, and results from in situ acoustic calibration runs can reduce the bias.

- Whereas the ocean bottom geoacoustic property of greatest influence at humpback whale frequencies (120-1800 Hz) is the type of sediment (quantified by the sediment grain size), it is the overall sediment thickness for the lower-frequency (10-200 Hz band) baleen whale calls.
- The GPL detector performance is significantly improved at HARP sites M, N, and H compared to the Santa Barbara Channel site. In particular, the false alarm rate is much lower since transient shipping noise, which can trigger the detector, is not prevalent in the recordings at the former sites. Because of ship noise and other sources of low-frequency ocean sound, the GPL detector false alarm rates are significantly higher for fin whale and Type D blue whale calls, as discovered in our LMR project.
- The spatial distribution of locations of calling animals during one experiment display statistically significant clustering for all call types using the nearest neighbor test. One call type shows significantly greater clustering than other call types. These results may reflect a behavioral context for this call type (e.g., call/counter-calling between a mother/calf pair).
- The time intervals between humpback whale calls are distinctly non-Poisson-distributed in nature, being better approximated by a log-normal distribution. These inter-call intervals for a single localized animal also are distinctly different than those discovered in human communications (e.g., time intervals between cell phone calls, time intervals between email transmissions, etc). The statistical distributions of inter-call intervals are environmentally-robust measures of the calling behavior of marine mammals.
- Localizing calling marine mammals using hydrophones with overlapping coverage (e.g., the Navy range hydrophones at baleen whale frequencies) eliminates the need to environmentally calibrate the call counts and thereby reduces significantly the uncertainties in the estimated animal densities obtained from passive acoustic recordings. Recordings from Navy range hydrophones also can be used to obtain high resolution estimates of the diving behavior of calling baleen whales, once certain aspects of the propagation that can cause signal fading and bias in the estimates are taken into account.
- Significant fading of received calls can occur at short ranges due multipath destructive interference. The narrowband phenomenon known as the Lloyd's mirror effect can have a remarkable impact on the detectability of broadband marine mammal calls at short range. For 20 Hz fin whale calls, destructive interference occurs at ranges shorter than about 500 m. The result is that the detection vs range curve for some marine mammal calls does not approach unity at short range. The decrease in detectability vs decrease in range information can be used to estimate the average depths of the calling animals. In addition, the notch created by the destructive interference of the direct and surface bounce arrivals is filled in by multipath returns from the ocean bottom, which can be used to estimate some of the geoacoustic properties of the ocean bottom.
- In situ calibration of small aperture arrays to correct for variations in sensitivity and frequency response across the array elements can be simply implemented in an automated way using the received sounds with high SNR from an acoustic source at known bearing. The resulting calibration corrections provide significantly improved direction-of-arrival estimates (much smaller variance in the estimates) for low frequency calls using highly adaptive beamforming methods.

IMPACT/APPLICATIONS

Passive underwater acoustic monitoring of marine mammal sounds is the Navy's primary method for characterizing the presence, distribution, and number of marine mammal species in a wide variety of environments, particularly those associated with Navy training ranges. Marine mammal population density estimates are particularly important in regions of Navy activities, or potential activities, in order to properly evaluate their potential impact under federal environmental legislation.

Understanding, and improving, this passive acoustic monitoring capability will decrease the environmental risk of Navy training exercises and other activities. Both the southern California Bight region and the area west of Kauai are areas of operational/training interest to the Navy. In addition, since these research efforts involve students in the field of marine bioacoustics at the Scripps Institution of Oceanography, as part of the thesis research, this project will help provide the Navy with the future generation of highly trained ocean bioacousticians aware of both Navy needs and environmental issues.

RELATED PROJECTS

The efforts in this project have been heavily leveraged with other programs. First, efforts in our Living Marine Resources project titled "Improving the Navy's Automated Methods for Passive Underwater Acoustic Monitoring of Marine Mammals" are focused on modifying the GPL processor for detecting a wide variety of marine mammal calls recorded by Navy range monitoring systems (the range hydrophones at the SCORE and PMRF ranges, and John Hildebrand's HARP packages in southern California near the SCORE range), and environmentally calibrating the resulting detected call counts in the near-SCORE HARP (sites M, N, and H) data. Call rate estimates from Tyler Helble's ONR Code 322-MMB project "Obtaining Cue Rate Estimates for Some Mysticete Species using Existing Data" can be used to derive animal density estimates from the calibrated call densities. Participation by senior-class undergraduate students from the UCSD Electrical and Mechanical Engineering departments was arranged by the UCSD Vice Chancellor of Academic Research. Algorithms from our "Glider-Based Passive Acoustic Monitoring Techniques in the Southern California Region", Code 322-MMB, have been used to automatically scan the data for marine mammal calls and other biological sounds.

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